RECLAMATION OF ACIDIFIED LAKES NEAR SUDBURY, ONTARIO BY NEUTRALIZATION AND FERTILIZATION

Ministry of the Environment
Ontario

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RECLAMATION OF ACIDIFIED LAKES

NEAR SUDBURY, ONTARIO

BY NEUTRALIZATION AND FERTILIZATION

by

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ABSTRACT

As part of the Sudbury Environmental Study, a study of the use of $Ca(OH)_2$ and $CaCO_3$ to neutralize acidic lakes near Sudbury, Ontario was begun in 1973 and is continuing to date. It was shown that the chemical treatment reduced total metal levels initially by up to 90% and increased lakewater pH and alkalinity. A combination treatment of $CaCO_3$ plus $Ca(OH)_2$ (as opposed to $Ca(OH)_2$ only) provided neutral conditions for a longer duration. Phytoplankton, zooplankton and zoobenthos standing stocks declined as a result of the rapid pH change. The stocks of phytoplankton increased to pre-treatment values within a matter of months but zooplankton and zoobenthos have shown no similar recovery to date. The taxonomic composition of the phytoplankton became more typical of non acid-stressed Shield lakes but zooplanktonic or zoobenthic composition did not change. A whole-lake nutrient enrichment experiment was carried out in an attempt to increase the biological standing stocks in a neutralized lake. Preliminary results indicated a rapid response of the phytoplankton to the nutrient additions.

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x—x—x MAB o—o MBS —— COMP

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3. Chlorophyceae
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5. Euglenophyceae
6. Chryptophyceae
7. Bacillariophyceae

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1. Cladocera
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3. Calanoida
4. Nauplius larvae
5. Rotifera

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SUMMARY AND CONCLUSIONS

1) The addition of neutralizing chemicals to acidic lakes has proven to be a feasible tool to raise lakewater pH, and increase alkalinity. Middle Lake, treated with $Ca(OH)_2$ and $CaCO_3$ maintained a near neutral pH for greater than 2 years, while Lohi Lake, treated twice with only $Ca(OH)_2$, dropped below a pH of 6 in well under 1 year after each treatment. Hannah Lake also received a combination treatment in 1975. Total copper and nickel levels were reduced initially by up to 90% in the lakes studied. The treatment reduced light penetration resulting in thermal stratification at shallower depths. Oxygen levels are not affected by the additions.

2) The data suggest a gradual regression of the neutralized lakes to their acidic state due to the continuing input of acidic material from the atmosphere and possibly the lake sediments. Although the duration of the treatment effects is not known, it appears that the addition of $CaCO_3$ and $Ca(OH)_2$ provides longer-lasting effects than $Ca(OH)_2$ alone, the $CaCO_3$ acting as a buffer through gradual dissolution.

3) A seasonal pattern of low pH and high free metal concentrations in the spring was observed due to the influx of acidic snow meltwater high in metal content. The increase in biological standing stock over the summer may aid in buffering the pH and complexing the free metals.

4) The effects of neutralization on the biological standing stocks included an immediate decrease in phytoplankton and zooplankton numbers. Zoobenthic standing stock also declined over pre-treatment values. Whereas phytoplankton stocks recovered within a matter of months, zooplankton numbers have shown no similar increase to date. Numbers of zoobenthos have recovered to their pre-treatment levels in Lohi Lake only.

5) Neutralization affected the taxonomic composition of the phytoplankton, dominance shifting from the acid-tolerant Pyrrophyta and Chlorophyceae to Chrysophyceae which are more typical of non acid-stressed Shield Lakes. No major changes were noted in zooplanktonic or zoobenthic taxonomic composition.

6) Phosphoric acid was used to increase total phosphorus levels in Middle Lake from 2.5 $\mu g\ l^{-1}$ to 9.0 $\mu g\ l^{-1}$. Using Lohi Lake as a control, it was shown that standing stocks of phytoplankton, zooplankton and to a lesser extent zoobenthos increased as a result of the nutrient additions. Changes in the taxonomic composition of the biota were observed even at these low rates of phosphorus addition. It was concluded that fertilization can act as a useful tool to speed biological recovery in a treated lake and increase the standing stocks of potential food sources for fish.

INTRODUCTION AND BACKGROUND

The existence of abnormally acidic lakes remote from industrial or mine tailing runoff is well documented in the greater Sudbury vicinity (Gorham and Gordon, 1960; Ontario Water Resources Commission, 1971; Beamish and Harvey, 1972; Conroy, Jeffries and Kramer, 1974). The affected lakes, lying on the sparingly soluble igneous or metamorphic bedrock common to the area, have low natural buffering capacities which are readily exhausted by even slight acid input. The acidic input is atmospheric in nature, resulting from the combination of airborne sulphur dioxide and water vapour (Brosset, 1973). The acid lake phenomenon is also well-known in Scandinavia (Oden, 1968; Oden and Ahl, 1970) and the N.E. United States (Likens, Borman and Johnson, 1972).

Acid lakes are chemically and biologically atypical compared to circumneutral Shield lakes and may show gradual loss of fish populations due to sublethal toxic effects and/or reproductive failure (Beamish, 1974; Beamish, Lockhart, Van Loon and Harvey, 1975). The need for study and management of these lakes is clear. In 1973, the Ministry of the Environment began an experimental program involving the neutralization of acidic lakes near Sudbury by direct addition of $Ca(OH)_2$ and $CaCO_3$ (Scheider, Adamski and Paylor, 1975). The ultimate objective of the project is the improvement of water quality such that a reproducing fishery can be sustained. The addition of neutralizing agents to lakes has long been practised as a means of altering water chemistry with a view toward improving productivity. Nees (1946) presented an account of lime treatment procedures used in central Europe beginning over a century ago. Much subsequent work has been conducted on humic lakes with low productivity which provides background for the Sudbury experiments (Hasler, Brynhildson and Helm, 1951; Waters, 1956; Bowling and Busbee, 1964).

Scheider et al (1975) showed that the chemical treatment neutralized the two acidic test lakes (Middle and Lohi) and reduced heavy metal levels substantially. A combination treatment, $Ca(OH)_2$ plus $CaCO_3$ gave longer lasting effects, the carbonate acting as a buffer through gradual dissolution. The immediate effect of the rapid pH change on the biology was to reduce standing stocks of phytoplankton, zooplankton and zoobenthos. Bacteria were the first to respond positively to the altered water chemistry. Numbers

increased and composition approached that of non-acid-stressed shield lakes shortly after treatment. Phytoplankton showed a similar response in the following year. Zooplankton and zoobenthic populations did not increase during the first year following treatment, probably due to a slower reproductive rate and the relative difficulty of recolonization.

Attention was turned in 1974 to methods of increasing the standing stock of components of the food chain in the neutralized lakes. Nutrient enrichment experiments in column enclosures (Scheider et al, 1975) showed that artificial fertilization with phosphorus acted to increase standing stocks of phytoplankton and zooplankton. Fertilization of lakes or ponds is a common procedure for increasing fish production (see reviews by Maciolek, 1954; Mortimer and Hickling, 1954; Winberg and Lyaknovich, 1965). Fertilization studies of Shield lakes are of particular interest (Langford, 1950; Smith, 1969; Schindler and Fee, 1974). Phytoplankton standing stocks increased in fertilized lakes in all studies; increases in zooplankton were noted by Langford (1950) and Smith (1969) and in zoobenthos by Smith (1969). Based on these results, a whole-lake fertilization experiment was conducted in Middle Lake in an attempt to raise the biological standing stock in a neutralized lake.

Neutralized Lohi Lake was monitored as the control for the Middle Lake enrichment. To prevent input of acidic water into Middle and to further test the effects of neutralization, upstream Hannah Lake was treated with $Ca(OH)_2$ and $CaCO_3$ in spring 1975. Clearwater Lake was monitored as the acidic control for Lohi.

DESCRIPTION OF STUDY AREA

Information on the geographical location, geology, land use and lake morphometry for study lakes (Hannah, Middle, Clearwater and Lohi) is given elsewhere (Scheider et al, 1975).

For convenience a brief summary is given in Table 1.

Table 1

Description of Study Area

	Middle Lake	Hannah Lake	Lohi Lake	Clearwater Lake
Bedrock geology	wanapitei quartzite	wanapitei quartzite	wanapitei quartzite	grenville gneiss and migmatite
Drainage basin area (km^2)	2.6	0.94	4.7	3.2
Lake Area (km^2)	0.27	0.27	0.41	0.72
Lake Volume ($m^3 \times 10^6$)	1.43	0.68	2.24	5.83
Mean depth (m)	5.3	3.6	5.5	8.1
Turnover time (yr)	1.3	2.5	1.1	4.4

METHODOLOGY

a) Field Methodology

Sampling frequencies for all parameters are summarized in Appendix 1. Physical, chemical and biological parameters were monitored at the deepest point on each lake unless stated otherwise. Temperature profiles were taken with a YSI telethermometer. Water transparency was measured with a standard 9" diameter Secchi disc. The euphotic zone was chosen as twice the Secchi disc (Vollenweider, 1969).

Two techniques were used to collect water samples for the chemical parameters listed in Appendix 1. During periods of spring and fall turnover water samples were taken by lowering a tygon tube to within one meter of lake bottom. The tube was clamped at water level, raised from the lower end by an attached line and emptied into a polyethylene bucket. During periods of thermal stratification, water samples were taken with a van Dorn bottle at regular intervals to 1m above bottom. An amount of water from each depth proportional to the volume of the stratum samples was added to a polyethylene bucket using a 1 l. graduated cylinder. Thus a single sample, integrated for the volumes of the various strata, was obtained and subsampled for each parameter. Analyses for oxygen were done on samples collected from each depth. Carbon dioxide analyses were done on samples taken at 1m below surface and 1m above bottom.

Phytoplankton and chlorophyll a samples were collected through the euphotic zone employing the tygon tube or the van Dorn method depending upon the thermal conditions of the lake. Phytoplankton samples were preserved with 2 ml Lugol's solution, then preconcentrated from 500 ml to 25 ml by allowing the plankton to settle out by gravity. Bi-weekly samples were counted (a.s.u. ml^{-1}) and identified (see taxonomy Reference marked *) except on Middle Lake where weekly samples were counted. Chlorophyll a samples were preserved with 1 ml $MgCO_3$ and filtered through 0.45μ Millipore paper under 40 cm Hg pressure. The papers were refrigerated in opaque Petri dishes prior to analysis.

Zooplankton samples were taken at four locations on each lake (Appendix 2) with a 1 m long conical tow net (30 cm mouth diameter, 76 mesh size). Samples were washed into 4 oz. jars, preserved with 1 ml of 37% formaldehyde per ounce of water and stored prior to counting. Samples from the four stations were combined to give a single sample for each lake, sub-sampled if necessary and counted. In Middle Lake each station was counted separately. Identification is after Pennak (1953) and Ward and Whipple (1966).

Zoobenthos was sampled using a modified (Burton and Flannagan, 1973) 30 cm by 30 cm tall (30 cm) Eckman dredge. Sampling locations are shown in Appendix 2. Each dredge haul was emptied into a sieve-screen device (520 μ) and cleared of debris by playing water over it. Organisms were hand-picked, counted, keyed (Pennak, 1953) and finally stored in 80% ethanol.

Precipitation samples were collected periodically at three locations, commencing in June, 1975. The rain samplers were of a simple, funnel-bottle type, designed to minimize evaporative loss. They were continuously open and thus collected total (wet and fry) fallout. The samplers were positioned approximately three feet above ground level in open areas at the laboratory site in Sudbury and on the shores of Hannah and Lohi Lakes.

The snow sampling device were continuously open plastic basins, positioned in the same locations as the rain samplers. When sampled, the entire basin was replaced and the contents melted, decanted and analysed. Both the funnels and plastic basins were washed with 10% HNO_3 and rinsed with distilled water prior to use. The funnels were fitted with course mesh screens to prevent macro-contaminants from entering the sample.

b) Laboratory Methodology

Samples for chemical analysis were submitted to the Ministry of the Environment Laboratories in Sudbury and Toronto. Standard analytical techniques were employed as outlined in APHA (1971), Ontario Ministry of the Environment (1975), O'Brian (1962), UNESCO (1966) and Lazrus, Hill and Lodge (1966).

c) Treatment with Calcium Hydroxide and Calcium Carbonate

The initial neutralization of Lakes Middle and Lohi is described by Scheider et al (1975). Lohi Lake, treated with $Ca(OH)_2$ in the fall of 1973 and July 1974, was observed to gradually regress to an acidic state and consequently was again neutralized (5.0×10^3 kg $Ca(OH)_2$) in May, 1975. Calcium carbonate (1.5×10^4 kg) was also added to provide a carbonate reservoir and ensure longer duration of near-neutral pH conditions. The rationale behind the choice of $Ca(OH)_2$ and $CaCO_3$ is given in Scheider et al (1975) and supported by Grahn and Hultbuerg (1975) who described the neutralizing capacities of 12 different lime products.

Hannah Lake was treated in June, 1975 with a combination of $Ca(OH)_2$ (1.3×10^4 kg) and $CaCO_3$ (7.5×10^3 kg) to further test the effectiveness of the method and to prevent the input of low pH water into Middle Lake. Dosage calculations and application techniques are described in Scheider et al (1975).

d) Nutrient Enrichment of Middle Lake

Previous whole-lake fertilization experiments (Schindler and Fee, 1974) on Canadian Shield lakes have conclusively demonstrated the important role of phosphorus in controlling phytoplankton standing stock. In the four study lakes, 1974 N:P ratios were well above 12, ranging from 30 to 140 (Middle Lake N:P = 95) and indicated that phosphorus was in short supply. Evidence from the enclosure studies (Scheider et al, 1975) demonstrated that additions of phosphorus alone could substantially increase phytoplankton and zooplankton standing stocks in a neutralized lake. Based on these data, phosphorus was the nutrient of choice for the Middle Lake enrichment experiments.

The phosphorus additions were designed to raise lakewater [P] to 10 $\mu g\ l^{-1}$ immediately and maintain this level for the duration of the year. Total annual additions necessary to achieve a spring [P] of 10 $\mu g\ l^{-1}$ were 32.3 kg. phosphorus as determined from the nutrient budget models summarized in Dillon and Rigler (1974). The initial addition of 11.1 kg P to bring the lake [P] up to 10 $\mu g\ l^{-1}$ was made on

June 19, 1975. Six further additions of 2.65 kg P were made bi-monthly to August 28, 1975 and a final addition of 5.30 kg was made on September 19, 1975.

The phosphorus was added in the form of H_3PO_4 because of its ready solubility and ease of handling. Additions were insufficient to depress lake pH.

RESULTS AND DISCUSSION

a) Optical Properties

The addition of $Ca(OH)_2$ and $CaCO_3$ to Hannah Lake caused a blue-green colouration, similar to the effect observed in Middle Lake after the 1973 $CaCO_3$ additions. As in the case of Middle Lake, the colour gradually disappeared over the course of the summer, the probable cause being the precipitation of suspended material. The treatment of Lohi Lake with $Ca(OH)_2$ and $CaCO_3$ did not result in the blue-green colour, even though volumetric additions of chemicals were similar in the three treated lakes (Table 2). The presence of the colour phenomenon in Middle and Hannah Lakes is not readily explained. Metal concentrations in Middle Lake and Hannah Lake were an order of magnitude higher than in Lohi Lake prior to neutralization and the amount of metal carbonates formed upon addition of treatment chemicals could have been correspondingly greater.

Hannah Lake Secchi transparency decreased in 1975 to a mean value of 6.2m (Table 3). The 1973 and 1974 mean values could not be properly calculated as Secchi disc was on the lake bottom on many occasions.

Middle Lake Secchi transparency in 1975 was 3.4m, a level similar to the 1974 value despite the tripling of chlorophyll a levels (1.1 mg m^{-3} in 1974 to 2.9 mg m^{-3} in 1975). The 1974 Secchi depth was likely affected by inorganic particulates caused by the chemical additions in the fall of 1973. The 1975 value reflects the increased chlorophyll a levels. The predicted Secchi depth from the equation:

$$S.D. = 5.21/\text{chl } \underline{a}^{0.41}$$

is 3.4m (Dillon, unpublished studies).

Table 2

Additions of $Ca(OH)_2$ and $CaCO_3$ to reclamation lakes (gm^{-3})

Lake	Date	$Ca(OH)_2$ added gm^{-3}	$CaCO_3$ added gm^{-3}
Hannah	June 1975	12.3	7.12
Middle	October 1973	13.9	9.46
Lohi	May 1975	2.03	6.08
Lohi	Total to date	12.4	6.08

Table 3

Reclamation Lake Secchi Disc Values (m)

Lake	Year	Mean Value (m)	Minimum Value (m)	Maximum Value (m)
Hannah	1973[1]	Lake Bottom	5.2	7.0
	1974[1]	" "	3.1	7.0
	1975	6.2	2.5	7.5
Middle	1973	11.0	6.0	13.2
	1974	3.0	1.2	6.7
	1975	3.4	2.3	5.3
Clearwater	1973	11.0	6.0	15.0
	1974	8.0	5.5	11.5
	1975	8.3	6.0	10.5
Lohi	1973	10.0	7.0	17.0
	1974	6.0	3.5	11.5
	1975	5.4	2.8	8.8

[1]*Mean values cannot be properly calculated as Secchi disc was on lake bottom on many occasions.*

The Secchi transparency of Lohi Lake was not affected by the $CaCO_3$ additions to the extent of Hannah and Middle Lake. The 1975 mean value (5.4m) was slightly less than the 1974 mean (6.0m). Secchi depth in the acidic control, Clearwater Lake, dropped by almost 3m, but this change is not significant at such great depths.

b) Temperature

Maximum summer surface temperatures were 22°C to 24°C in the study lakes. All lakes with the exception of Hannah were thermally dimictic (Fig. 1) as in previous years (Scheider et al, 1975). Hannah Lake, because of its shallow depth, was homothermous.

Scheider et al (1975) have shown that thermal stratification occurred at shallower depths in Middle and Lohi the summer following chemical additions probably because of reduced light penetration. This phenomenon was not observed after the 1975 neutralization of Hannah Lake because the reduction in light penetration was not great enough to significantly alter the thermal properties of the water.

c) Oxygen and Carbon Dioxide

All lakes were well oxygenated with bottom water oxygen levels >7 mg l^{-1} (Fig. 2). Chemical neutralization had no effect on the oxygen regimes nor did the fertilization of Middle Lake result in depletion of bottom water O_2 levels at any time during thermal stratification. The oxygen profiles were generally of a positive heterograde nature, showing O_2 maxima just below the metalimnion. The exception is Hannah Lake, which because of its thermal homogeneity showed an orthograde oxygen structure.

Mean surface water (MBS) CO_2 levels ranged from 1.4 mg l^{-1} to 1.9 mg l^{-1} in the neutralized lakes. Clearwater lake had a higher mean value of 6.7 mg l^{-1} in accord with its acidic pH. Bottom water (MAB) CO_2 levels in Hannah Lake were the same as surface water values because of the continuous mixing of the lake. The other three lakes showed elevated CO_2 values in the bottom water as a result of the decomposition of organic matter below the metalimnion (Table 4).

Table 4

Carbon dioxide (mg l^{-1}) in the reclamation lakes

Lake		Mean $[CO_2]$ (mg l^{-1})	Min. $[CO_2]$ mg l^{-1}	Max. $[CO_2]$ mg l^{-1}
Hannah	MBS	1.9	1.0	4.5
	MAB	1.9	1.5	2.5
Middle	MBS	1.4	0.5	2.0
	MAB	5.5	1.0	9.0
Clearwater	MBS	6.7	4.5	10
	MAB	8.9	6.5	15
Lohi	MBS	1.7	0.5	2.5
	MAB	7.5	2.0	11

The neutralization of Hannah Lake caused a reduction in CO_2 levels as the CO_2 - HCO_3^- - CO_3^{2-} system was shifted toward HCO_3 by the chemical additions. This phenomenon has been previously observed in neutralized Middle and Lohi Lakes (Scheider et al, 1975).

d) Ionic and Heavy Metal Chemistry

Prior to treatment the study lakes were characterized as soft and poorly buffered with unusually low pH values (Scheider et al, 1975). Sulphate was the dominant ionic constituent and levels of copper and nickel were among the highest recorded in the Sudbury vicinity. The immediate effects of the 1973 neutralization of Middle and Lohi Lakes were to raise pH to neutrality, increase alkalinity and reduce levels of heavy metals by up to 90%. Table 5 summarizes pertinent chemical characteristics of the four lakes for 1973-75. Complete 1975 chemical data are given in Appendix 3.

Although 1975 sampling methods differed from those employed in previous years and results are not completely comparable, certain trends are evident. In Middle Lake, decreases in pH, alkalinity and calcium were observed in 1975 (Fig. 3). Combined with the increases in total copper and total nickel (Fig. 4) these results suggest a gradual regression of Middle Lake to its pre-treatment state. This trend is to be expected for two reasons. Precipitation to the lake continues to be acidic in nature and high in Cu and Ni levels (Table 6) compared to the lakewater. Secondly, sediment neutralization, occurring gradually at the expense of bicarbonate in the lakewater, may act to deplete the lake's buffering capacity and acidify the lake. Sediment release of Cu and Ni may occur if acidic conditions prevail at the sediment-water interface (Sadana, 1976).

This same trend had previously been observed in Lohi Lake (Scheider et al, 1975) necessitating retreatment of the lake with $Ca(OH)_2$ in July 1974. By the end of May 1975, Lohi Lake pH was 5.6. The longer duration of neutral conditions in Middle Lake was attributed to the effectiveness of the $CaCO_3$ additions in establishing a bicarbonate buffer system assuming both lakes have similar inputs of acidic material.

Table 5

Summary of chemistry of reclamation lakes

1973-1975 mean values (mg l^{-1})

	1973[1]	1974[1]	1975[2]
Hannah Lake			
pH (range)	4.3-4.9/4.3-4.6	4.1-4.5/4.1-4.5	6.7-7.3
alkalinity	0.4/0.4	0.0/0.0	7.0
calcium	13.7/11.4	11.4/11.5	20.1
copper	-/1.06	1.12/1.13	0.058
nickel	-/1.58	1.85/1.87	0.350
Middle Lake			
pH (range)	4.3-5.3/4.3-4.9	6.7-7.3/6.3-7.0	6.0-6.9
alkalinity	0.40/0.60	6.9/8.7	4.2
calcium	9.8/9.6	14.2/14.4	13.1
copper	0.090/0.496	0.068/0.083	0.116
nickel	0.280/1.07	0.339/0.373	0.492
Clearwater Lake			
pH (range)	4.1-5.2/4.3-4.6	4.1-4.4/4.1-4.4	4.2-4.5
alkalinity	0.6/0.4	0.0/0.0	0.0
calcium	6.2/6.4	5.5/5.5	5.5
copper	0.090/0.092	0.110/0.093	0.106
nickel	0.250/0.278	0.286/0.275	0.274
Lohi Lake			
pH (range)	4.3-4.8/4.3-5.7	5.5-6.8/5.7-6.2	6.7-7.2
alkalinity	0.6/2.6	2.2/2.7	5.4
calcium	6.2/6.0	7.9/7.7	8.9
copper	0.090/0.080	0.042/0.053	0.042
nickel	0.250/0.245	0.192/0.213	0.158

[1]Data are MBS/MAB [2]volume weighted

Table 6

Chemistry of Precipitation falling on reclamation lakes

Ranges given in mg l^{-1}

Site[1]	Form	pH	Total Cu	Total Ni	Number of Events
Laboratory	Rain	2.5-4.5	0.34-0.59	0.075-0.27	6
	Snow	4.4-4.6	0.78-3.30	0.26 -0.83	2
Hannah	Rain	3.8-6.6	0.12-0.48	0.015-0.26	4
	Snow	4.4-4.5	0.98-1.50	0.30 -0.50	2
Lohi	Rain	2.5-4.5	0.13-0.28	0.015-0.090	7
	Snow	4.4-4.5	0.34-0.52	0.15 -0.18	2

[1]*Location of site shown in Appendix 2.*

This supposition will not be proven until chemical budgets are constructed. Lohi Lake was treated with a combination of $Ca(OH)_2$ and $CaCO_3$ in June 1975. The pH rose to neutrality, alkalinity and calcium levels increased and copper and nickel concentrations dropped. Table 7 summarizes the immediate pre and post-neutralization chemistry.

The addition of $Ca(OH)_2$ and $CaCO_3$ to Hannah Lake altered water chemistry in much the same way as it had in Middle and Lohi Lakes. The pH rose to neutrality and alkalinity, calcium and hardness increased as a direct result of the additions (Table 7). Levels of the heavy metals Cu, Ni, Zn, Mn and Co were reduced by 96%, 77%, 82%, 45% and 59% respectively. Control Clearwater Lake did not show any marked changes in chemical characteristics in 1975 compared to previous years. Figures 3 and 4 show pH and total copper levels (1973-1975) for the study lakes.

Marked seasonal variations in pH and free metals occurred in 1975, especially in Middle Lake. Values of pH were lowest (6.0) shortly after the lake opened in May and rose steadily to 6.7-6.9 by mid-summer, remaining at these levels until ice-on in November.

Lohi Lake showed a similar spring pH depression and the beginning of an increase, pH rising from 5.0 after ice-off to 5.6 by the end of May 1975. Any further seasonal trend in pH was overshadowed by the June neutralization. Neither Hannah nor Clearwater Lakes exhibited any similar trend.

A spring pH depression in the surface waters of Norwegian lakes has been reported by Hagen and Langeland (1973) and by Hultberg (1975) for Swedish lakes. Yan (1975) recorded a pH increase of almost one unit from May to September in acidic Carlyle Lake near Sudbury. This phenomenon is probably due to the input of acidic material from the snow meltwater. The pH of snow overlying the reclamation lakes was measured as 4.4-4.6 (Table 6) in January and February 1976. Beamish and Harvey (1972) found snow pH to vary from 2.9-3.8 in the La Cloche Mountain area near Sudbury. Kramer (1973) measured snow pH values of 3.8-6.1 in the Sudbury vicinity.

Table 7

Immediate pre and post-neutralization chemistry (mg l^{-1})

of Lohi and Hannah Lakes (1975)

	Lohi Lake		Hannah Lake	
	Pre	Post	Pre	Post
pH	5.6	7.1	4.8	7.0
Alkalinity	2.0	6.0	1.0	5.0
Calcium	7.0	8.0	13.0	19.0
Total Copper	0.066	0.049	0.96	0.042
Total Nickel	0.250	0.180	1.30	0.30
Free Copper	0.040	0.011	0.860	0.012

A spring maximum in free Cu concentration was noted in Middle Lake. Values of free Cu dropped steadily from a maximum of 0.085 mg l^{-1} (May 1976) to 0.010 mg l^{-1} (October 1976). Free zinc showed spring and fall maxima. These seasonal variations in free metal levels are probably related to three phenomena: the input of metals from the snow melt-water, the low lakewater and snow pH and the increase in biological standing stock (and hence organic matter and complexing capacity) during the summer period. Snow samples (taken January and February 1976) had total Cu concentrations of 0.52-3.3 mg l^{-1} and total zinc levels of 0.035-0.72 mg l^{-1}. At the snow pH of 4.4-4.6, much of the metal was probably in the free state. Kramer (1973) reported values of 0.025-2.47 mg l^{-1} total Cu and 0.071-0.400 mg l^{-1} total zinc in snow collected in the Sudbury vicinity. Free metal levels declined in mid-summer probably because of the increased complexing capacity of the lakewater due to increased biological standing stock.

A seasonal cycle of low spring pH and high free metal concentrations could be especially detrimental to spring spawning fish and benthic organisms that emerge shortly after ice-off. Reproductive failure due to low pH has been identified as one mechanism contributing to the extinction of fish populations in several lakes near Sudbury (Beamish and Harvey, 1972; Beamish, 1974; Beamish et al, 1975). In Scandinavia, Jensen and Snekvik (1972) and Almer (1972) reported that the increased acidity of lakes and rivers detrimentally affected reproductive success and caused loss of fish populations. Bell (1971) working with 10 species of aquatic insects, found them to be most sensitive to low pH levels during emergence.

Middle and Hannah Lakes had 1975 mean concentrations of Na and Cl two to six times higher than measured in previous years. This did not occur in Lohi and Clearwater. The cause of the elevated levels is unknown.

e) Fertilization and Nutrient Chemistry

Scheider et al (1975) suggested that phosphorus was stripped from the water column of treated lakes, possibly by a precipitation

mechanism as are heavy metals. However, phosphorus concentrations were too close to the detection limit of the analytical method to obtain accurate estimates. There is no evidence that the 1976 treatment of Hannah or Lohi Lakes affected phosphorus levels in any manner because levels were near detection limit. This contradicts the findings of Hasler et al (1951), Waters (1956) and Ahl et al (1969) in Wilander and Ahl (1972) who found lime treatment to increase total phosphorus in the water column. However, the lakes studied by Hasler et al (1951) and Waters (1956) were humic in nature. The precipitation and subsequent breakdown of the organic matter could have been a source of phosphorus. Ahl et al (1969, in Wilander and Ahl, 1972) reported that the lime itself was a significant source of phosphorus.

Fertilization in Middle Lake raised total phosphorus levels from 2.5 $\mu g\ l^{-1}$ to 9.0 $\mu g\ l^{-1}$ after the first addition, with a mean summer concentration of 8.1 $\mu g\ l^{-1}$. Mean summer total phosphorus levels for the non-fertilized lakes were 3-4 $\mu g\ l^{-1}$. The phosphorus budget for the fertilization period is summarized in Table 8. The input from land runoff is based on the phosphorus loading in precipitation assuming 0 and 100% of the precipitation that fell reached the lake. The sewage input is calculated from knowledge of the number of dwellings on the lake and the methodologies summarized in Dillon and Rigler (1975) assuming that 0 and 100% of the phosphorus in the sewage reached the lake. The fertilization with H_3PO_4 was, therefore, the major source of P input to the lakes (73-99%), even assuming maximum input from other sources. Table 9 shows the destination of the added phosphorus.

The lake outlet did not flow during the fertilization period. The loss to the sediments was 60-66% of input, a figure similar to the 62% reported by Schindler et al (1971) for fertilized Lake 227 in the E.L.A.

Scheider et al (1975) found Kjeldahl N to decrease slightly after treatment in Lohi Lake, possibly due to the precipitation of organic matter. No evidence for this trend was seen in the spring 1975 treatments of Lohi and Hannah Lakes. In fact, all lakes showed increased Kjeldahl N levels over 1974 values. The predominant form

Table 8

Phosphorus budget of fertilized Middle Lake

(June 19, 1975 - Oct. 14, 1975)

	Precipitation on Lake Surface	Land Runoff	Sewage from dwellings	Fertilization	Total
Input to lake in mg m^{-2}	0.32	0.0-1.67	0.0-42.2	118.8	119-163
Input in kg.	0.09	0.0-0.45	0.0-11.5	32.3	32.4-44.3
% Total Input	0.19-0.27	0.0-1.0	0.0-25.9	72.9-99.8	100

Table 9

Destination of phosphorus additions (kg) in Middle Lake

(June 19, 1975 - Oct. 14, 1975)

Amount in lake June 19, 1975	Total Additions	Amount in Lake water Oct. 14, 1975	Loss to Outflow	Presumed Loss to Sediments
3.6	32.4-44.3	16.5	0	19.5-31.4

of nitrogen in the lakewater was Kjeldahl N in Lohi and Clearwater Lakes (75% and 61% of total N). Nitrate was the more common form in Middle and Hannah Lakes (52% and 68% of total N).

f) Biology

Phytoplankton and Chlorophyll a

Prior to neutralization all study lakes had standing stocks somewhat lower than those reported for non acid-stressed, oligotrophic lakes in southern Ontario (Michalski et al, 1973; Christie, 1968) but similar to those of other acidic lakes in the Sudbury area (Johnson and Owen, 1966; Conroy, 1971). The majority of the standing stock was made up of Chlorophyceae, Dinophyceae and Cryptophyceae, with Chrysophyceae also significant. The importance of Pyrrophyta and the absence of Bacillariophyceae is thought to be atypical and indicative of acid stressed conditions. The taxonomic compositions were similar to those found in acidic Swedish lakes, where Chlorophyta and Pyrrophyta with some Chrysophyceae make up the bulk of the biomass (Almer et al, 1974; Hornstrom et al, 1973).

The addition of $Ca(OH)_2$ and $CaCO_3$ to Middle and Lohi Lakes in the fall of 1973 caused immediate declines in phytoplankton standing stock (Scheider et al, 1975). The June, 1975 neutralization of Hannah Lake had a similar effect, reducing the standing stock from 139 a.s.u. ml^{-1} (immediately prior to treatment) to 0.3 a.s.u. ml^{-1} (immediate post-treatment). This may be a direct toxic effect of the $Ca(OH)_2$, lethality caused by changes in pH or CO_2 (Whipple 1948 in Waters, 1956), or the removal of algae by a flocculation and precipitation phenomenon as observed for the heavy metals (Cohen and Hannah, 1971).

Smaller additions of $Ca(OH)_2$ and $CaCO_3$ have not affected the phytoplankton to the same extent. The July, 1974 treatment of Lohi raised lakewater pH from 5.6 to 6.7 and phytoplankton standing stock increased. The May, 1975 treatment of Lohi Lake raised lakewater pH from 5.6 to 7.1 with the standing stock decreasing from 182 a.s.u. ml^{-1} to 70 a.s.u. ml^{-1} (immediate post-treatment).

Phytoplankton standing stocks increased to pre-treatment levels the summer following the fall 1973 neutralization of Middle and Lohi Lakes (Table 10).

The recovery after the spring, 1975 treatment in Hannah Lake was complete by midsummer. However, in no case did the standing stocks significantly increase over the pre-treatment levels. This was to be expected as phytoplankton standing stock (as [chlorophyll a]) has been shown to be correlated with [P] by Sakamoto (1966) and Dillon and Rigler (1974) and phosphorus levels did not increase after neutralization.

The addition of phosphorus as H_3PO_4 to Middle Lake resulted in an increase in the phytoplankton biomass from the 1974 mean (June-October) of 126 a.s.u. ml^{-1} to a 1975 mean of 703 a.s.u. ml^{-1}. Mean summer concentration of chlorophyll a increased from 1.1 $\mu g\ l^{-1}$ to 2.4 $\mu g\ l^{-1}$. Phytoplankton standing stocks decreased in the neutral control, Lohi Lake. Previous fertilization studies of Shield lakes have shown that an increase in phytoplankton standing stock occurs within weeks after nutrient addition (Langford, 1948; Smith, 1969; Schindler et al, 1971).

Changes in taxonomic composition as well as in biomass occurred with each form of treatment applied (Fig. 5). Scheider et al (1975) showed Chrysophyceae to comprise the majority of the phytoplankton standing stock in the mid-summer and fall in neutralized lakes. The spring 1975 neutralization of Hannah Lake had a similar effect on taxonomic composition, Chrysophyceae assuming dominance by mid-summer with Myxophyceae and Bacillariophyceae also significant. The typical acid lake dominants (Dinophyceae, Cryptophyceae and Chlorophyceae) remained prevalent in Clearwater Lake.

Among the Chrysophyceae, *Dinobryon*, *Epipixis* and an unidentified chrysomonad were important. *Chlamydomonas* was significant among the Chlorophyceae of all lakes, although *Oocystis* was more prominent in acidic Clearwater Lake. *Peridinium* was the dominant genus of Dinophyceae found in Clearwater Lake and *Mastigocladus* was important among the Myxophyceae in the neutral lakes.

Table 10

1973-1975 Midsummer Standing Stocks of Phytoplankton

(July-September Mean and Range in a.s.u. ml^1)

	1973		1974		1975	
	mean	range	mean	range	mean	range
Hannah	100	49-168	155	28-473	133	42-269
Middle	135	32-230	193	43-405	977	206-3667
Clearwater	107	54-193	201	70-542	229	86-351
Lohi	241	52-545	355	173-696	154	108-221

The fertilization of Middle Lake altered the taxonomic composition of the phytoplankton, dominance shifting from Chrysophyceae (prior to nutrient addition) to Chlorophyceae and then to the blue-green Mastigocladus. Chrysophyceae again assumed importance in the fall. In the neutral control, Lohi Lake, the midsummer phytoplankton were dominated by Chrysophyceae. Previous whole lake fertilization experiments have shown diverse affects on taxonomic composition. Langford (1948) observed Bacillariophyceae and the flagellate Dinobryon to increase in importance in two fertilized shield lakes in Algonquin Park, Ontario. Smith (1969) and Michalski and Conroy (1972) found the blue-green Anabaena to become dominant after fertilization. Schindler et al (1971, 1973) found the Chlorophyceae to be midsummer dominants in 3 of the 4 years of fertilization experiments conducted on Lake 227 in the E.L.A. Myxophyceae were important in mid-summer in one year only. Fall and winter dominance was by Chrysophyceae and Cryptophyceae. Reasons for these variable results are not yet clear.

In summary, neutralization caused an initial decline in phytoplankton standing stock but in all cases biomass recovered to pretreatment levels within a matter of months. A change in taxonomic composition occurred in the neutralized lakes with Chrysophyceae assuming mid-summer dominance. Fertilization caused an increase in standing stock and shifted the dominance from Chrysophyceae to Myxophyceae.

Zooplankton

Prior to neutralization, the mid-summer standing stock of crustacean zooplankton in the four study lakes range from 1.5 l^{-1} organisms to 45.8 l^{-1} (Table 11). These numbers fall in the mid to lower end of the range of values reported for five non acid-stressed lakes of similar morphometry in the Experimental Lakes Area (Patalas, 1971). The taxonomic composition in the study lakes was not diverse (4-5 species per lake) and dominance was by the cladoceran Bosmina longirostris with nauplius larvae important among the Cyclopoida. Rotifers were numerically significant only in Lohi Lake. However, a numerical

Table 11

Mid-summer Standing Stocks (numbers l^{-1}) of

Crustacean zooplankton and rotifers

(July - September 1973-1975)

Crustacea

	1973		1974		1975	
	Mean	Range	Mean	Range	Mean	Range
Hannah	1.5	0.7- 3.0	1.4	0.3- 4.4	0.2	0.0- 0.4
Middle	17.3	0.3-74.1	0.6	0.2- 1.8	2.6	0.3- 6.6
Clearwater	10.3	2.0-21.6	34.2	2.3-63.7	4.4	3.4- 5.6
Lohi	45.8	16.1-82.2	2.4	0.2- 6.9	1.6	0.3- 4.3
5 Lake ELA (1971)			6.6 - 54			

Rotifera

	1973		1974		1975	
	Mean	Range	Mean	Range	Mean	Range
Hannah	0.2	0.0- 0.9	0	0.0-0.0	0.05	0.0- 0.07
Middle	0.05	0.0- 0.3	0	0.0-0.0	0.29	0.0- 1.1
Clearwater	0.6	0.0- 1.8	0	0.0-0.0	48.1	15.7-87.3
Lohi	30.4	0.0-77.7	0	0.0-0.0	2.2	0.0- 4.9

assessment over-emphasizes the importance of rotifers to the standing stock as their individual biomasses (dry weight) may be several orders of magnitude smaller than that of a crustacean zooplankton (Schindler and Noven, 1971).

The 1973 treatment of Lohi and Middle Lakes reduced the standing stocks of crustacean zooplankton and numbers did not return to former levels in 1974. The neutralization of Hannah Lake in 1975 caused a similar decline and numbers have not recovered to pretreatment levels. The decline in standing stock was probably due to the rapid pH change or associated phenomena. The slow recovery compared to the phytoplankton is probably related to the relative difficulty of recolonization and longer life cycle of the zooplankton. Standing stocks also declined after the 1975 treatment of Lohi Lake although numbers did increase by mid-summer. As with the phytoplankton, it would seem that smaller pH changes had less of an effect on zooplankton numbers. It is noteworthy that numbers of crustacean zooplankton also declined in the acidic control, Clearwater Lake. Numerical changes in treated lakes have been interpreted taking this into consideration.

In fertilized Middle Lake, mid-summer crustacean zooplankton numbers increased over 1974 values, with a mean of 2.6 organisms l^{-1}. Smith (1969) found zooplankton standing stocks to increase after fertilization with maximum biomass occurring 2-4 years after nutrient addition. He observed temporary depressions in zooplankton standing stock when blooms of *Anabaena* formed, presumably because of the poor grazing provided (Edmondson, *in* Smith, 1969). Langford (1948) also reported slight increases in crustacean zooplankton numbers after fertilization.

The effect of neutralization and fertilization on rotifers is difficult to judge. Rotifers were present in all lakes in 1973, absent from all lakes in 1974 and re-appeared in 1975 with maximum numbers in acidic Clearwater Lake. Numbers were lower in fertilized Middle Lake than in the neutral control, Lohi Lake, although both Smith (1969) and Langford (1948) report significant increases in rotifer standing stocks after nutrient additions. Annual and

seasonal fluctuations of rotifers are common (Pennak, 1949; Schindler and Noven, 1971). It is also worth noting (Likens and Gilbert, 1970) that rotifers may pass through 76µ mesh, resulting in erratic estimates of numbers present.

Certain regularities and trends in the taxonomic composition of the crustacean zooplankton were apparent from 1973-1975 regardless of the treatment employed. In 1973, Cladocera were numerically prominent in all lakes with nauplius larvae important and Calanoida absent. In 1974, Cladocera continued to dominate the zooplankton in both neutralized and acidic control lakes. Nauplius larvae were not found but Calanoida were present, numerically important in August and September in all lakes. Cyclopoida were prominent in all lakes in June. In 1975, Cladocera were important in spring and fall (except in Hannah). Nauplius larvae were again present, but assumed importance at different times in each lake. Cyclopoida were present in the neutralized lakes and Calanoida in fertilized Middle Lake only.

The prominent species of Cladocera were *Bosmina longirostris* and *Chydorus sphaericus* in all years. Similarly, among the Cyclopoida copepodids and *Cyclops vernalis* were always important. Copepodids and *Epishura lacustris* were the prominent forms of Calanoida.

Neutralization seemed to have no consistent effect on the number of species present with numbers increasing after the 1973 treatment of Lohi Lake but decreasing after the neutralization of Middle Lake 1973, Lohi Lake 1975 and Hannah Lake 1975. In fertilized Middle Lake, the number of species recorded increased to seven, whereas the number of species decreased in the other lakes in 1975 indicating that perhaps fertilization had an effect.

In summary, it would seem that neutralization decreased the mid-summer crustacean zooplankton stocks and no recovery to pre-treatment levels was evident. Standing stocks did increase in response to fertilization, possibly because of increased food supply. The taxonomic composition of the zooplankton followed certain patterns regardless of the form of treatment employed, although fertilization seemed to

have increased the number of species present in Middle Lake. Three species formed the bulk of the zooplankton adult biomass in 1973-1975.

Zoobenthos

Zoobenthic standing stocks prior to neutralization ranged from 654 organisms m^{-2} to 1172 m^{-2}, comparable to the numbers found by Hamilton (1971) for non acid-stressed lakes of similar morphometry in the E.L.A. Chironomidae were numerically dominant in all lakes (>85% of total numbers m^{-2}) and certain acid sensitive taxa were notably absent (Mollusca, Ephemeroptera). The taxonomic composition agreed with observations of benthos in acidic Scandinavian lakes (Hagen and Langeland, 1973; Grahn, Hultberg and Landner, 1974).

Numbers of zoobenthic organisms in 1974 decreased in neutralized Middle and Lohi Lakes whereas they remained constant or increased in the acidic control lakes (Scheider et al, 1975). A similar decline was noted in the 1975 benthos of neutralized Hannah Lake. The rapid pH change likely had a detrimental effect as insect larvae are known to be sensitive to changes in pH, especially during emergency (Bell, 1971). The accumulation of Cu and Ni in the sediments due to precipitation from the water column and the temporary decline of phytoplankton following treatment may have been partially responsible for the decrease in benthic numbers observed the following year. The possibility that undissolved $CaCO_3$ smothered the zoobenthos can probably be dismissed as zoobenthic stocks declined when $Ca(OH)_2$ alone was used.

As a word of caution, it should be noted that numbers of zoobenthos change seasonally due to emergence. Year to year comparisons of standing stocks should be done using the results of surveys taken at the same time of year to minimize interpretation problems.

Increases in standing stock were observed in both Middle and Lohi Lakes in 1975, whereas numbers decreased in acidic control Clearwater Lake (Fig. 7). However, recovery to pre-treatment levels was achieved in Lohi Lake only, despite the June addition of $Ca(OH)_2$ and $CaCO_3$. The

fertilization of Middle Lake probably played only a minor role in increasing the numbers of benthic organisms, as the time between the commencement of phosphorus additions and the August benthos survey was too short for the benthos to respond to the increased food supply. The November figures perhaps better reflect the fertilization effects. Smith (1969) reported an increase in benthic biomass after each addition of fertilizer with maximum numbers occurring 2-4 years after the additions. Rather, the increase in Middle Lake zoobenthos is probably the beginning of a post-neutralization return to pretreatment numbers.

Taxonomic composition remained basically unchanged in 1973-1975 with Chironomidae numerically dominant in all lakes (80% total numbers). The single exception to this was the 1974 survey of Lohi Lake, when Oligochaeta were numerically dominant. Hamilton (1971) found Chironomidae and Chaoborinae numberically dominant in non acid-stressed lakes of similar morphometry in the E.L.A.

The number of taxa present in each lake varied from year to year, showing no consistent pattern with neutralization. In fertilized Middle Lake, the number of taxa increased and Ceratopogonidae, Oligochaeta and Anisoptera were recorded in 1975 for the first time. The lack of speciation precludes a more complete discussion of treatment effects on zoobenthic composition.

SUMMARY

The addition of neutralizing chemicals caused changes in the optical, thermal and chemical properties of the lakes. Important effects included the reduction of light penetration resulting in thermal stratification at shallower depths, increased pH and alkalinity levels and a reduction of lakewater total Cu and Ni by up to 90%. Effects on the biota included an immediate decline in phytoplanktonic and zooplanktonic standing stocks. Numbers of zoobenthos also decreased over pre-neutralization values. Whereas the phytoplankton standing stocks increased to pre-treatment levels within a matter of months, numbers of zooplankton did not show a similar recovery.

The phytoplankton taxonomic composition was altered by neutralization, Pyrrophyta and Chlorophyceae being replaced by Chrysophyceae as mid-summer dominents. No changes in zooplankton or zoobenthos composition were noted after treatment.

Two temporal trends of note were observed. The data suggested a gradual regression of neutralized Middle Lake to its acidic state, with decreases in pH, alkalinity and calcium and increases in total Cu and Ni. This was perhaps to be expected as precipitation falling on the lakes was acidic in nature with high Cu and Ni levels. Sediment neutralization may also have contributed to the depression in lakewater pH. Secondly, a seasonal pattern of low pH and elevated free copper in the spring was observed. This was probably due to the influx of snow meltwater of low pH and high metal content.

The nutrient enrichment of Middle Lake with H_3PO_4 increased [P] from 2.5 $\mu g\ l^{-1}$ to 9.0 $\mu g\ l^{-1}$, with a mean summer value of 8.0 $\mu g\ l^{-1}$. Effects on the biota included increases in phytoplanktonic, zooplanktonic and possibly zoobenthic standing stocks. Phytoplankton taxonomic composition was altered with Mastigocladus assuming midsummer dominance. The number of species of zooplankton increased and 3 new taxa of benthos were recorded.

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APPENDIX 1: SAMPLING FREQUENCY 1975

Code

1. pH, alkalinity, hardness, conductivity, calcium, magnesium.
2. CO_2, O_2.
3. total phosphorus, nitrate N, Nitrite N, ammonia N, Kjeldahl N.
4. sulphate, sodium, potassium, chloride, silica.
5. total copper, total nickel, total zinc, manganese, iron, cobalt, cadmium, lead, chromium, aluminum, free copper, free zinc.
6. chlorophyll a, phytoplankton.
7. zooplankton.
8. zoobenthos.

Lake	Code	Sampling Schedule
Middle	1,2,3,4,6	Weekly 12/5 - 2/9 Bi-weekly 2/9 - 11/11
	5	Bi-weekly 12/5 - 11/11
	7	Bi-weekly or Tri-weekly 12/5 - 11/11
	8	July, August, November.
Hannah	1,2,6	Weekly 12/5 - 2/9 Bi-weekly 2/9 - 11/11
	3,4,5	Bi-weekly 12/5 - 11/11
	7	Bi-weekly or tri-weekly 12/5 - 11/11
	8	August and November.
Lohi	1,2,6	Weekly 12/5 - 2/9 Bi-weekly 2/9 - 11/11
	3,4,5	Bi-weekly 12/5 - 11/11
	7	Bi-weekly or Tri-weekly 12/5 - 11/11
	8	August, November
Clearwater	1,2,6	Weekly 12/5 - 2/9 Bi-weekly 2/9 - 11/11
	3.4.5	Bi-weekly 12/5 - 11/11
	7	Bi-weekly or Tri-weekly 12/5 - 11/11
	8	August, September

APPENDIX 2: SUMMARY OF CHEMICAL DATA (mg l^{-1})

Middle Lake (May 12 - Nov. 11/76)

Parameter	Number of Samples	Mean Value	Minimum Value	Maximum Value
pH	21	6.6	6.0	6.9
alkalinity	21	4.2	2.5	6.0
hardness	21	43	41	46
conductivity	21	138	134	148
calcium	20	13.1	12.0	14.0
sulphate	18	40.9	33.0	56.0
sodium	17	4.8	4.3	5.3
potassium	17	1.54	1.40	1.65
silica	15	1.85	1.6	2.2
chloride	15	7.4	6.5	8.1
magnesium	21	2.9	2.0	4.0
total phosphorus	13	0.0081	0.0025	0.016
nitrate N	18	0.29	0.05	0.57
nitrite N	18	0.004	0.001	0.007
ammonia N	18	0.028	<0.010	0.090
Kjeldahl N	18	0.272	0.160	0.470
total nickel	14	0.116	0.068	0.220
total copper	13	0.492	0.410	0.570
total zinc	14	0.047	0.031	0.120
manganese	14	0.211	0.17	0.29
iron	14	0.125	0.066	0.420
cobalt	14	0.012	<0.001	0.030
cadmium	14	< .003	-	-
lead	14	< .005	-	-
chromium	14	< .003	-	-
aluminum	9	0.123	0.070	0.230
free copper	10	0.029	0.010	0.085
free zinc	9	0.024	0.011	0.045

APPENDIX 2: Continued

Hannah Lake (June 10 - Nov. 11/75)

Parameter	Number of Samples	Mean Value	Minimum Value	Maximum Value
pH	17	7.0	6.7	7.3
alkalinity	17	7.0	3.0	8.5
hardness	17	66	61	69
conductivity	17	206	195	215
calcium	15	20.1	19.0	21.0
sulphate	9	57.7	43.0	75.0
sodium	9	8.3	7.7	8.7
potassium	9	2.0	1.8	2.1
silica	8	1.2	1.0	1.6
chloride	9	16.2	15.0	17.0
magnesium	15	3.9	3.0	4.0
total phosphorus	8	0.0036	0.001	0.008
nitrate N	9	0.51	0.41	0.64
nitrite N	9	0.009	0.006	0.012
ammonia N	9	0.065	0.090	0.030
Kjeldahl N	9	0.230	0.130	0.350
total nickel	10	0.35	0.30	0.40
total copper	11	0.058	0.030	0.110
total zinc	9	0.032	0.024	0.043
manganese	11	0.18	0.12	0.23
iron	10	0.087	0.019	0.150
cobalt	10	0.009	<0.004	0.013
cadmium	11	<0.003	-	-
lead	11	<0.003	-	-
chromium	11	<0.003	-	-
aluminum	10	0.096	0.048	0.190
free copper	8	0.011	0.006	0.015
free zinc	8	0.023	0.009	0.045

APPENDIX 2: Continued

Lohi Lake (June 2 - Nov. 11/76)

Parameter	Number of Samples	Mean Value	Minimum Value	Maximum Value
pH	18	6.9	6.7	7.2
alkalinity	18	5.4	4.5	6.5
hardness	18	27	24	29
conductivity	18	80	78	81
calcium	18	8.9	7.0	10
sulphate	11	24.3	20.0	27.0
sodium	11	1.7	1.4	2.1
potassium	11	0.76	0.65	0.94
silica	10	2.2	1.9	2.5
chloride	11	2.0	1.7	2.1
magnesium	18	1.0	1.0	1.0
total phosphorus	11	0.0038	0.001	0.008
nitrate N	11	0.053	<0.010	0.150
nitrite N	11	0.002	0.001	0.004
ammonia N	11	0.019	<0.010	0.040
Kjeldahl N	11	0.168	0.110	0.250
total nickel	12	0.161	0.12	0.24
total copper	12	0.042	0.026	0.056
total zinc	12	0.025	0.018	0.037
manganese	12	0.16	0.11	0.25
iron	11	0.096	0.057	0.150
cobalt	12	0.004	<0.002	0.008
cadmium	12	<0.001	-	-
lead	12	<0.003	-	-
chromium	12	<0.002	-	-
aluminum	10	0.101	0.043	0.210
free copper	9	0.009	0.003	0.018
free zinc	7	0.016	0.007	0.035

APPENDIX 2: Continued

Clearwater Lake (June 2 - Nov. 11/76)

Parameter	Number of Samples	Mean Value	Minimum Value	Maximum Value
pH	19	4.3	4.1	4.5
alkalinity	19	0.0	0.0	0.0
hardness	18	18	17	21
conductivity	19	86	78	92
calcium	18	5.5	5.0	6.0
sulphate	10	25.1	21.0	28.0
sodium	10	1.6	1.3	2.0
potassium	10	0.75	0.60	0.85
silica	9	1.99	1.90	2.00
magnesium	18	1.5	1.3	1.7
total phosphorus	10	0.0031	0.001	0.012
nitrate N	7	0.06	0.04	0.09
nitrite N	10	0.001	<0.001	0.001
ammonia N	10	0.027	0.010	0.050
Kjeldahl N	10	0.142	0.080	0.200
total nickel	11	0.274	0.250	0.310
total copper	10	0.106	0.091	0.120
total zinc	10	0.048	0.039	0.076
manganese	11	0.291	0.270	0.310
iron	10	0.131	0.091	0.250
cobalt	11	0.010	0.008	0.012
cadmium	11	0.001	<0.001	0.002
lead	8	0.007	0.004	0.009
chromium	11	<0.003	-	-
aluminum	10	0.442	0.370	0.510
free copper	8	0.061	0.027	0.094
free zinc	7	0.042	0.021	0.069

Figure 1

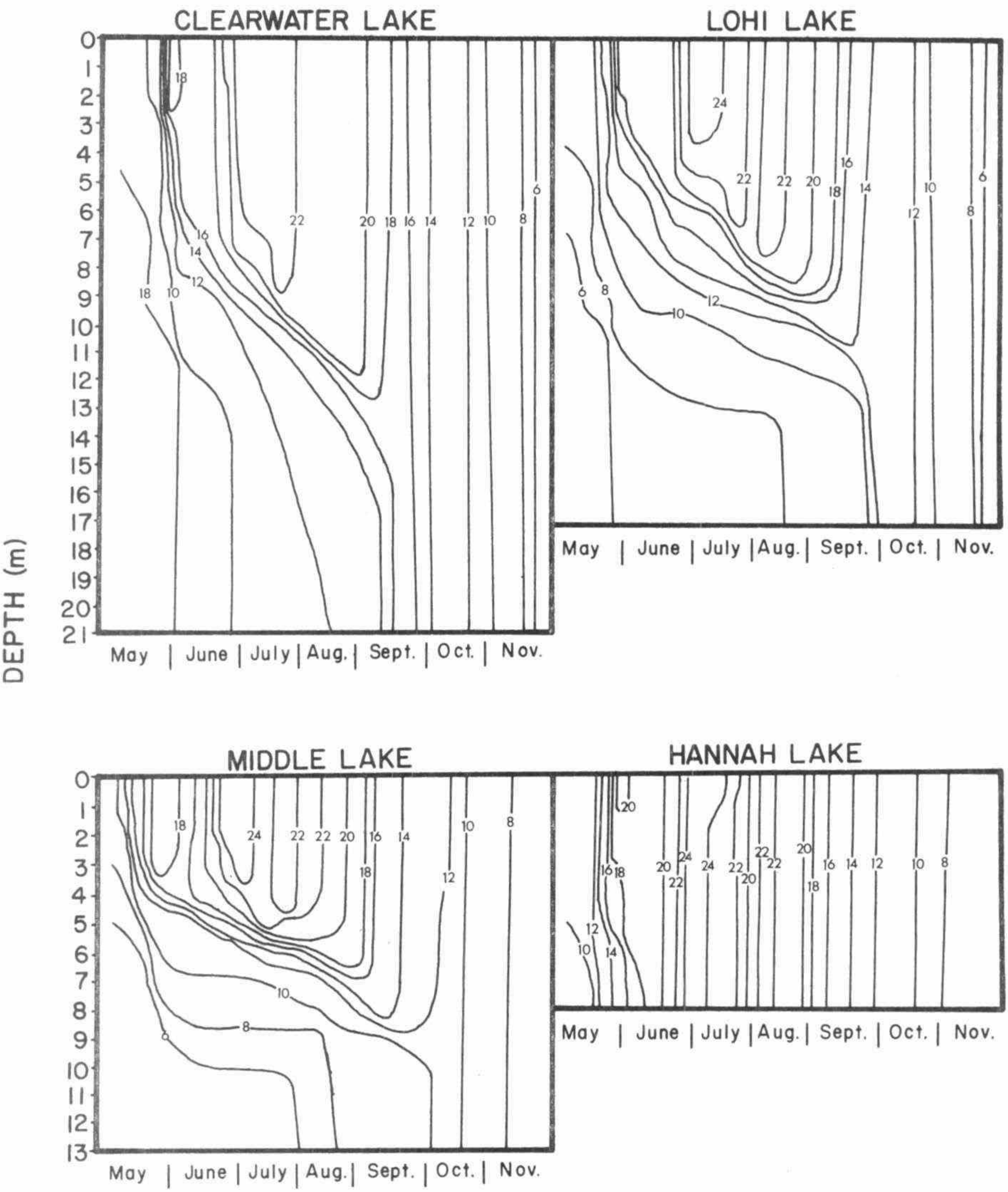

CLEARWATER LAKE
LOHI LAKE
MIDDLE LAKE
HANNAH LAKE
DEPTH (m)
May | June | July | Aug. | Sept. | Oct. | Nov.

Figure 2

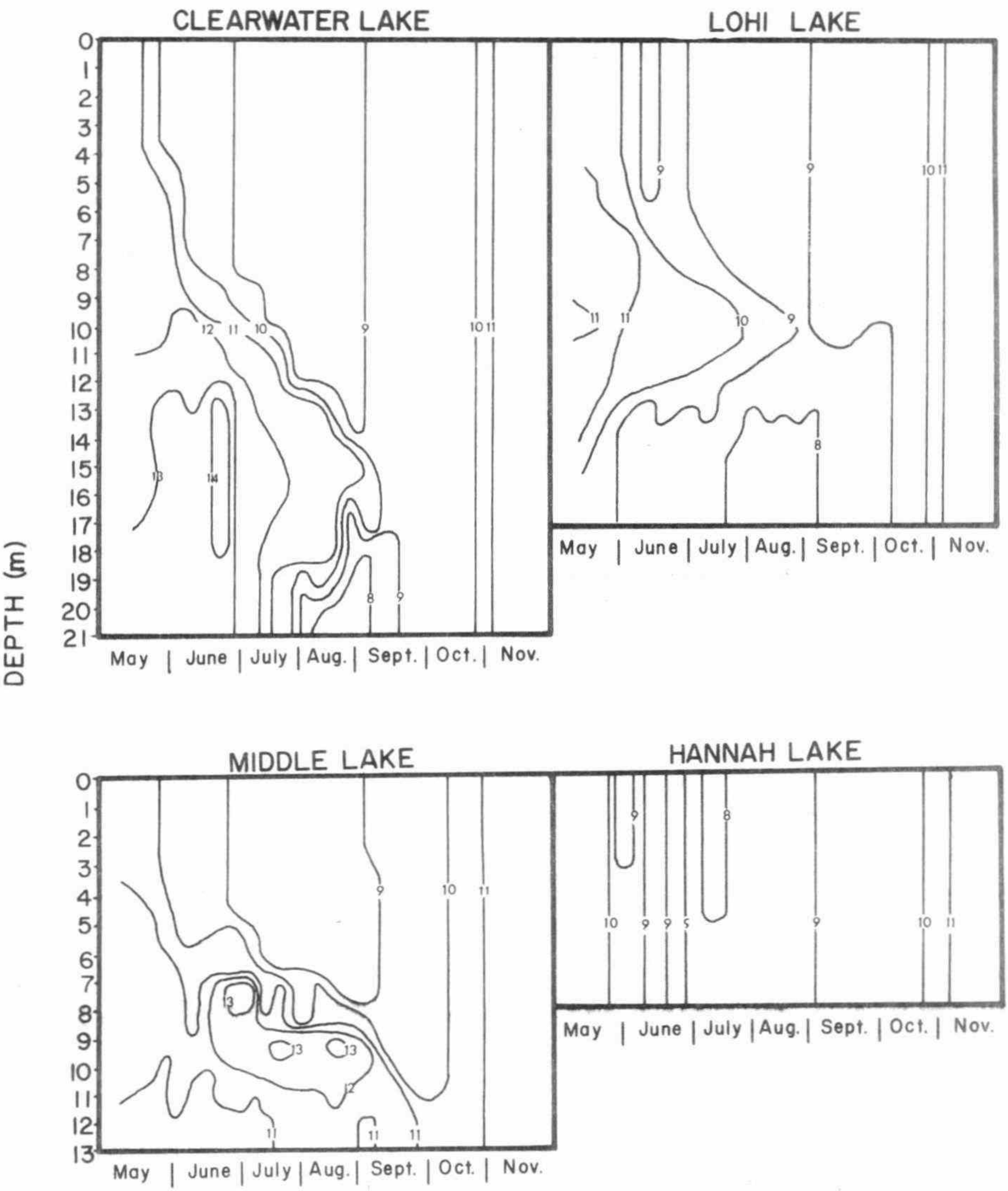

CLEARWATER LAKE
LOHI LAKE
MIDDLE LAKE
HANNAH LAKE
DEPTH (m)
May | June | July | Aug. | Sept. | Oct. | Nov.

Fig. 3a

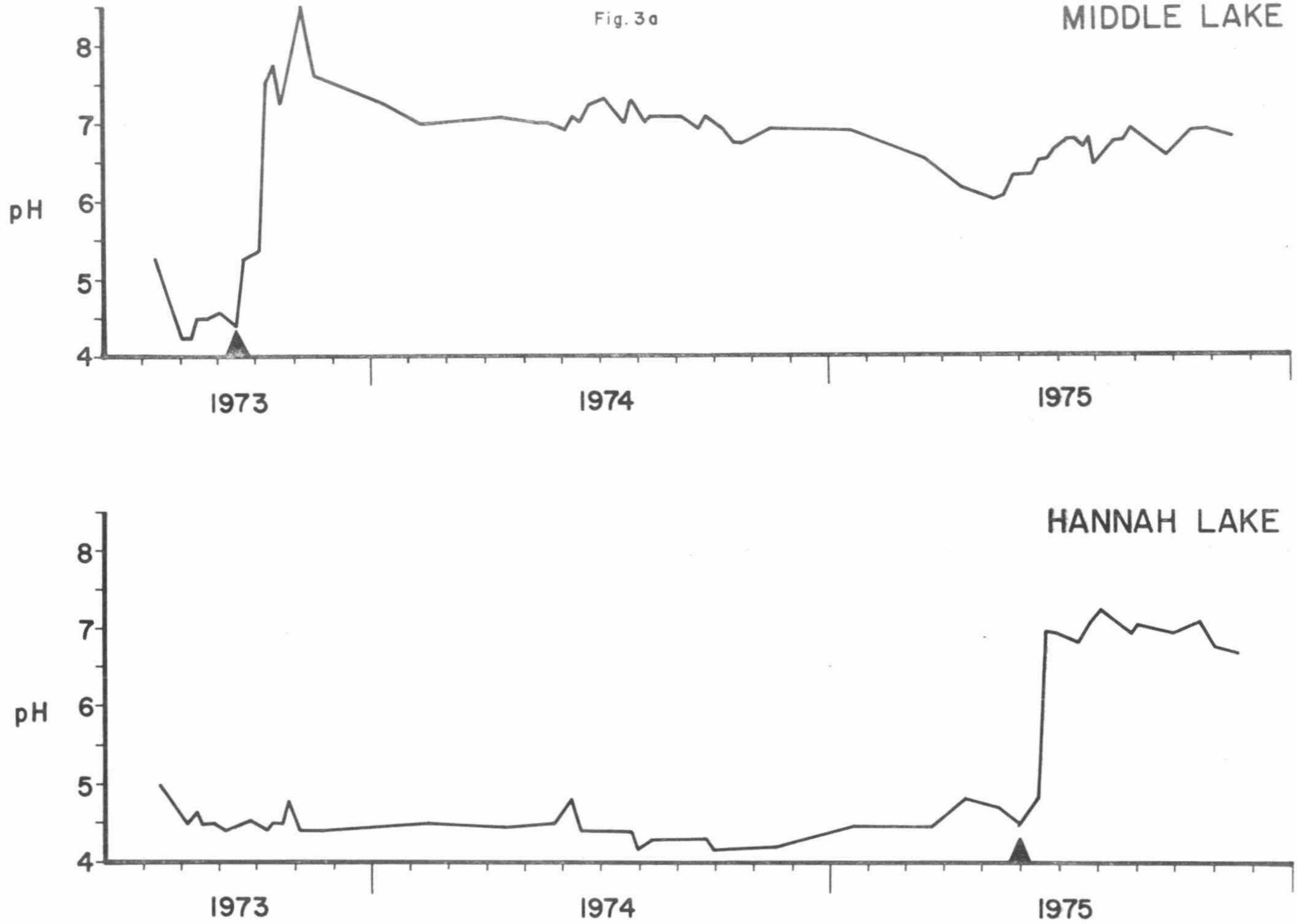

MIDDLE LAKE
pH
8
7
6
5
4
1973
1974
1975
HANNAH LAKE
pH
8
7
6
5
4
1973
1974
1975

Fig. 3b

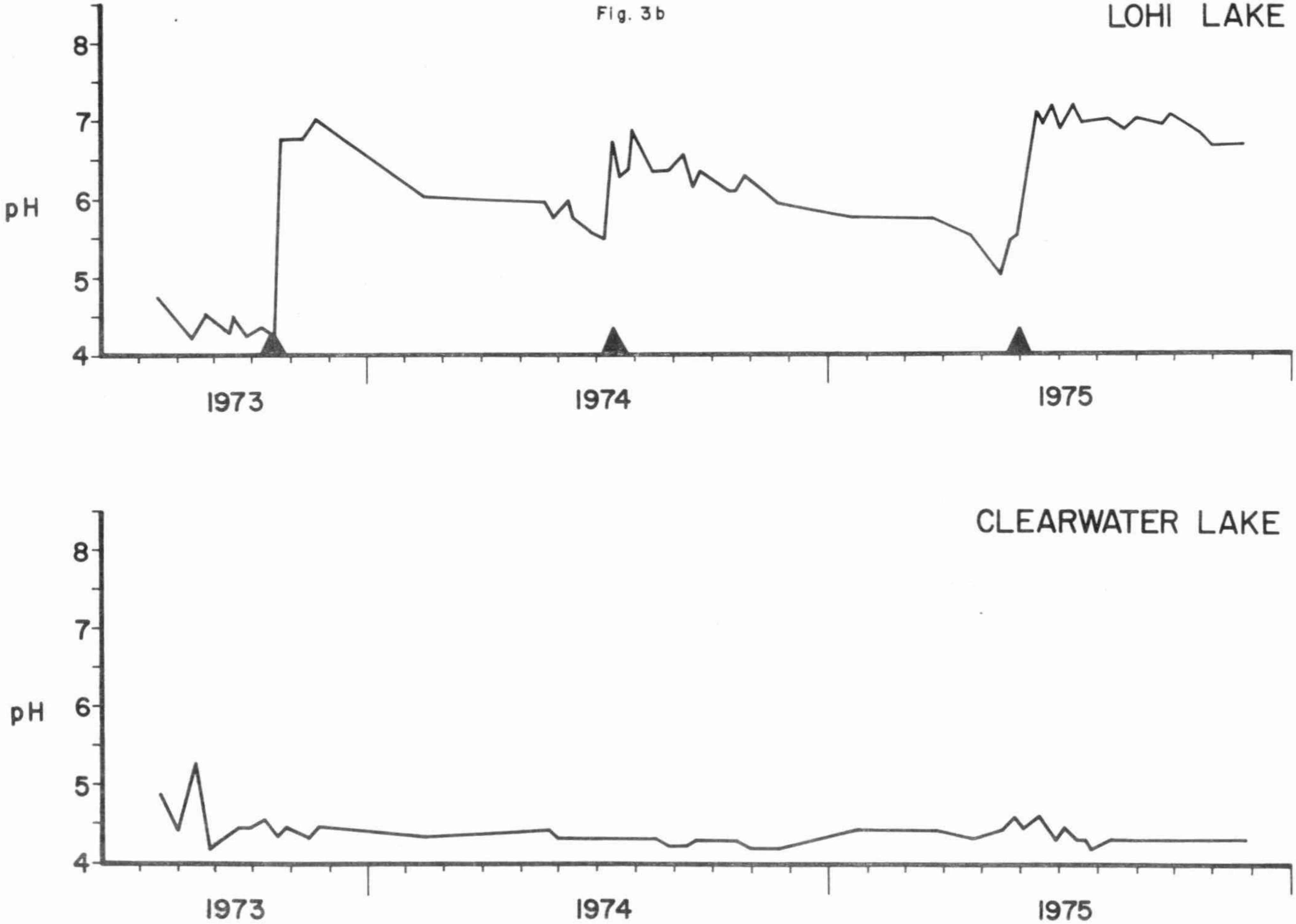

LOHI LAKE
pH
8
7
6
5
4
1973
1974
1975
CLEARWATER LAKE
pH
8
7
6
5
4
1973
1974
1975

Fig. 5a

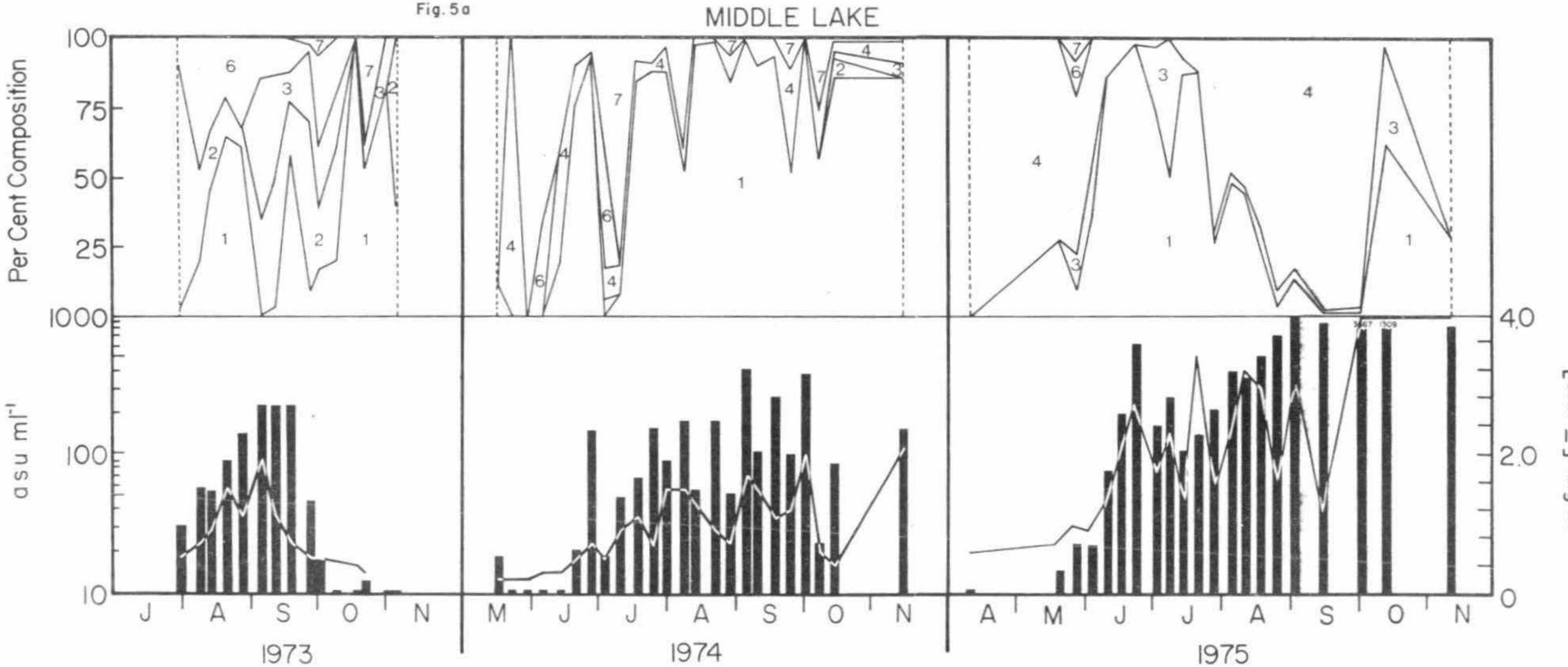

MIDDLE LAKE
Per Cent Composition
100
75
50
25
1000
100
10
asu ml⁻¹
[Chl. a] mg m⁻³
4.0
2.0
0
J A S O N
M J J A S O N
A M J J A S O N
1973
1974
1975

Fig. 5b

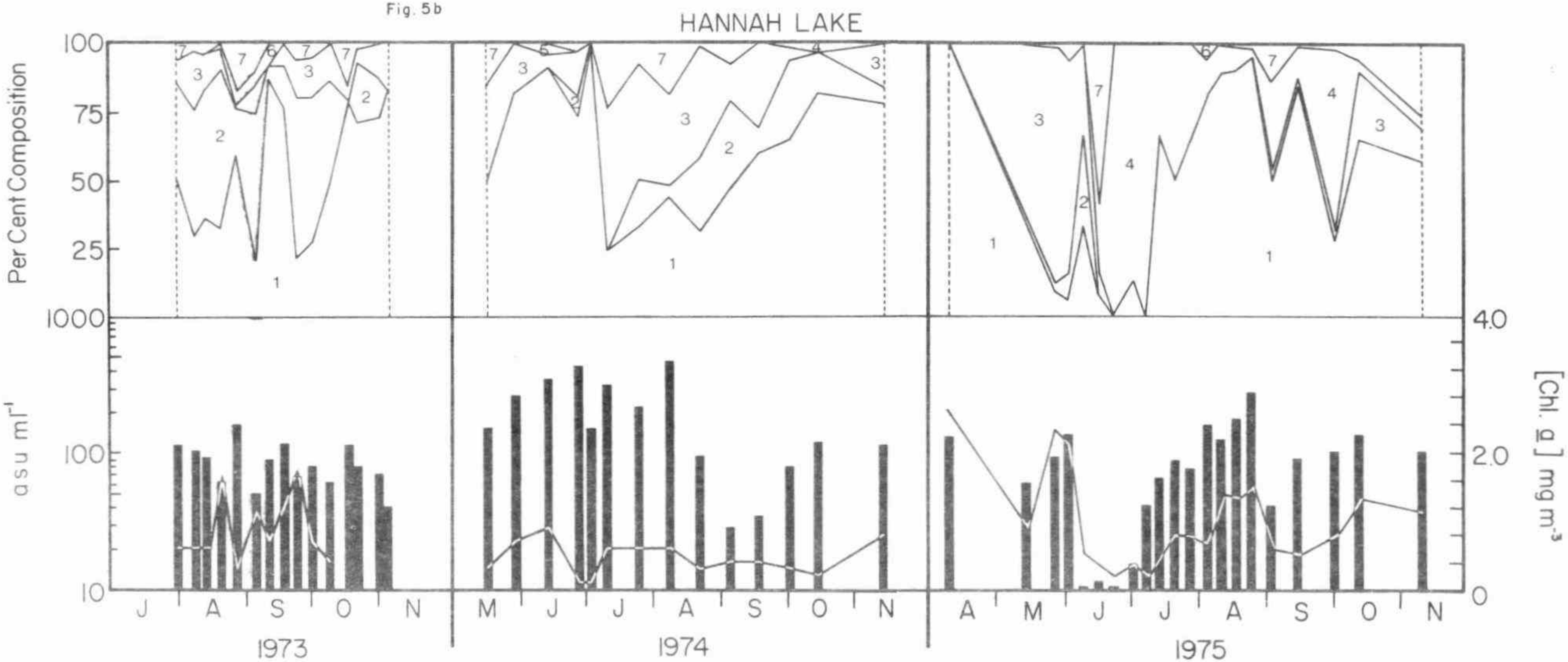

HANNAH LAKE
Per Cent Composition
100
75
50
25
1000
100
10
asu ml⁻¹
4.0
2.0
0
[Chl. a] mg m⁻³
J A S O N
1973
M J J A S O N
1974
A M J J A S O N
1975

Fig. 5c

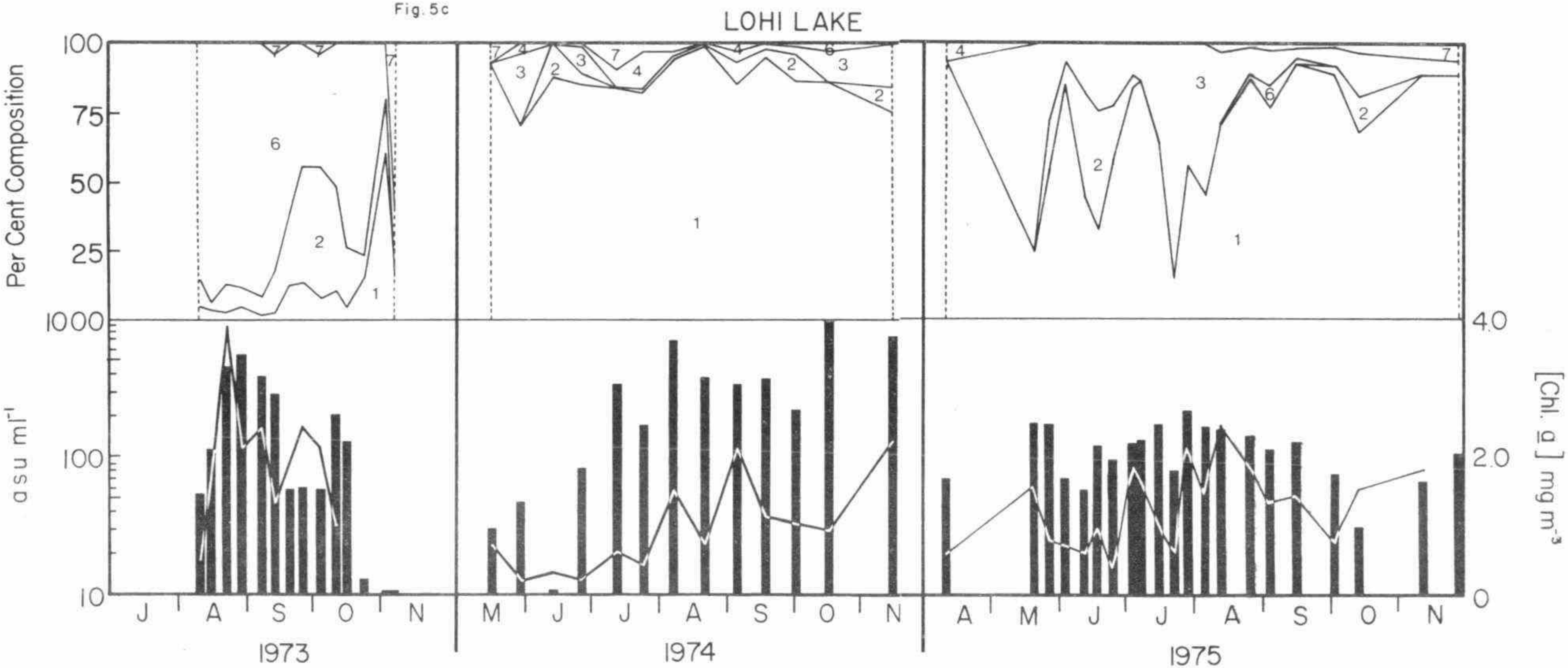

LOHI LAKE
Per Cent Composition
100
75
50
25
1000
100
10
asu ml⁻¹
[Chl. a] mg m⁻³
4.0
2.0
0
J
A
S
O
N
1973
M
J
J
A
S
O
N
1974
A
M
J
J
A
S
O
N
1975

Fig. 5d

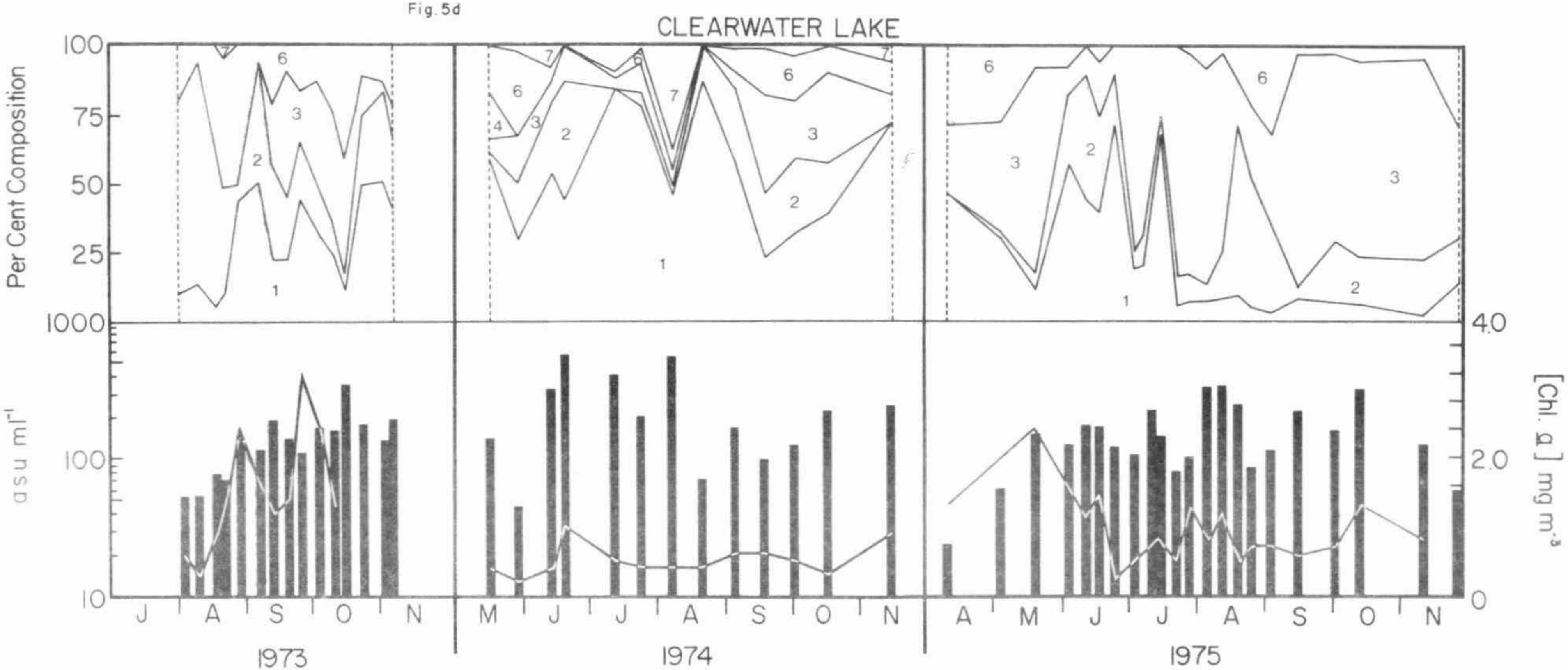
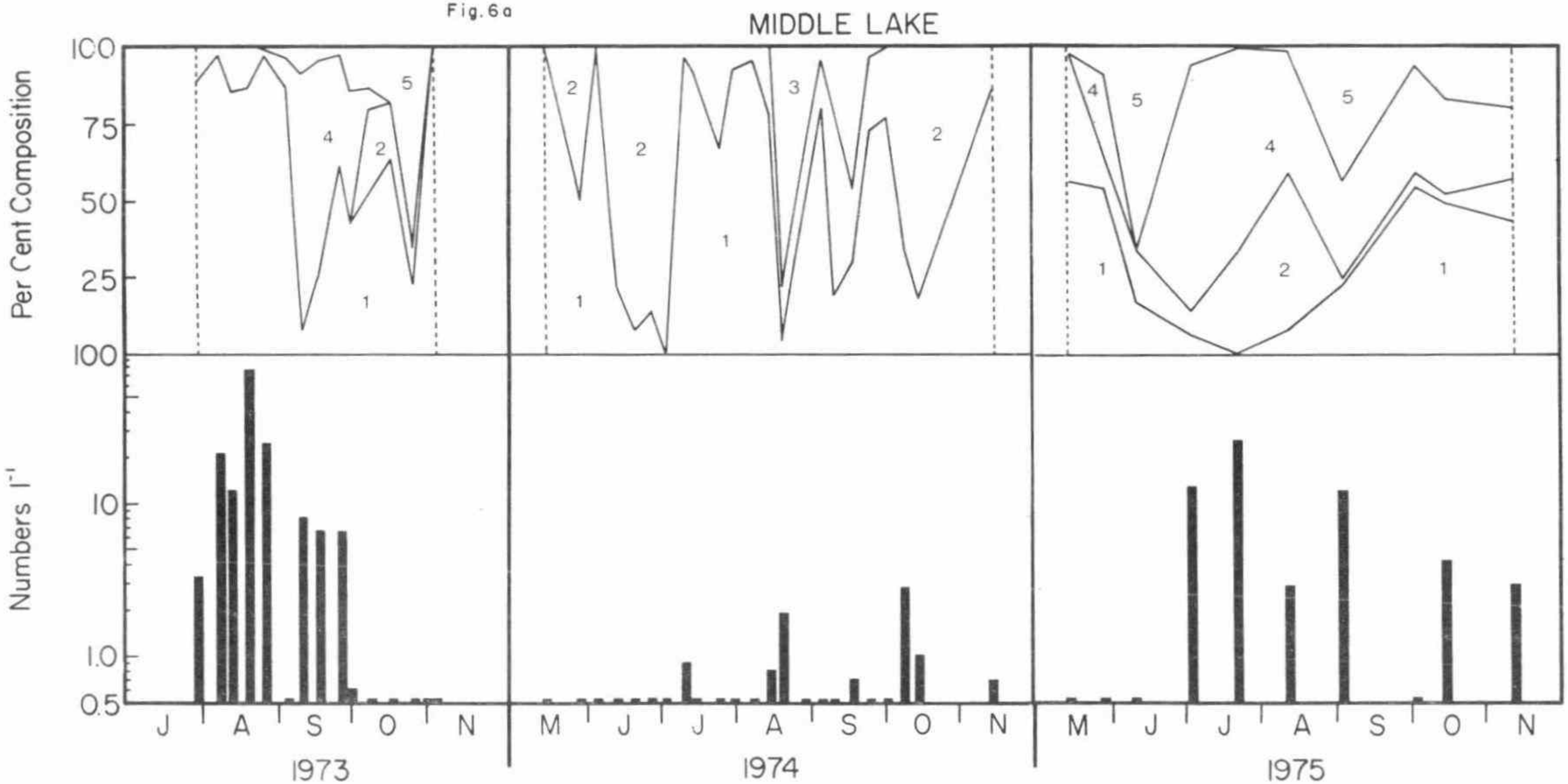
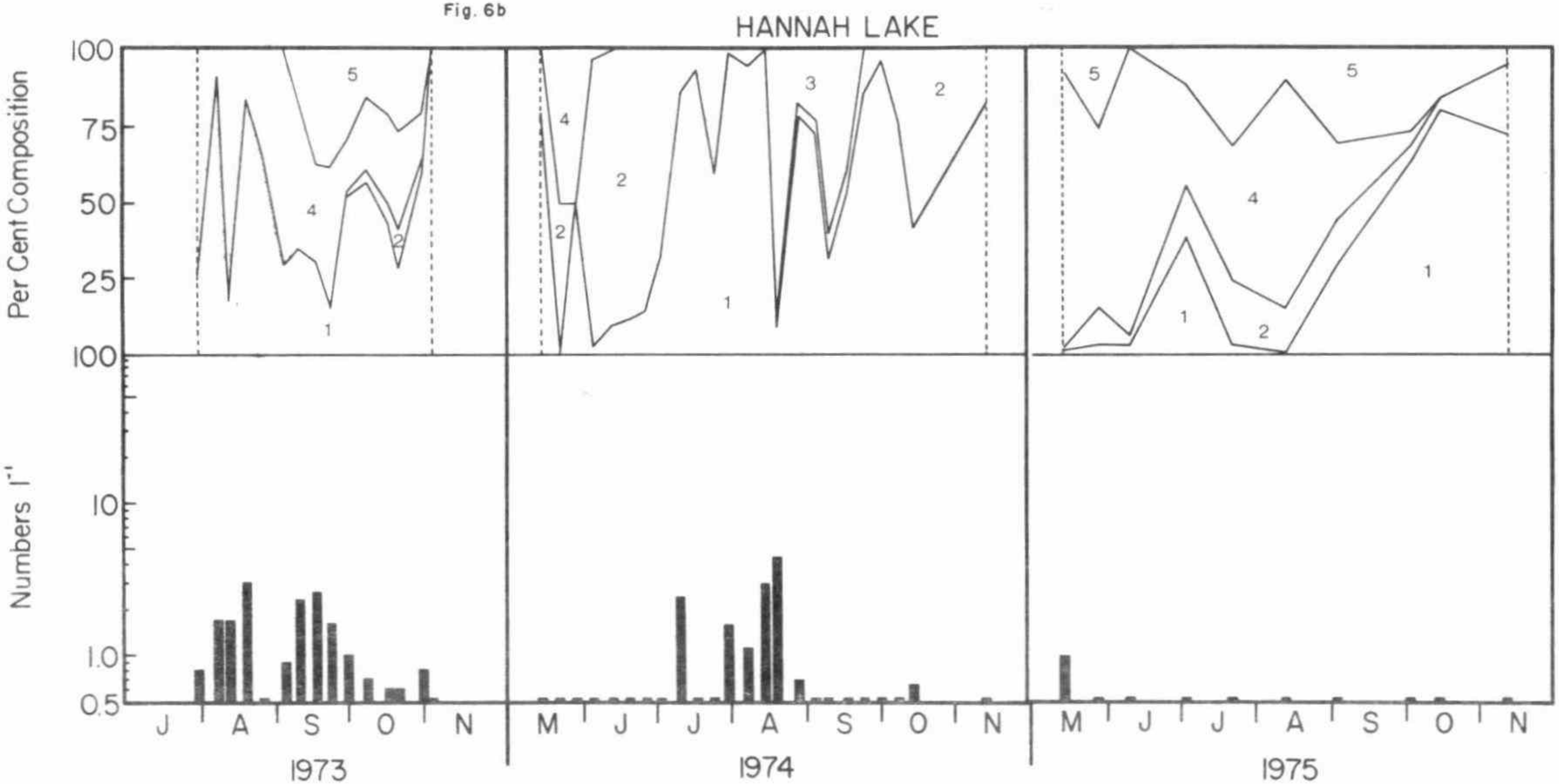

CLEARWATER LAKE
Per Cent Composition
100
75
50
25
1000
100
10
asu ml⁻¹
4.0
2.0
0
[Chl. a] mg m⁻³
J A S O N
M J J A S O N
A M J J A S O N
1973
1974
1975

Fig. 6a



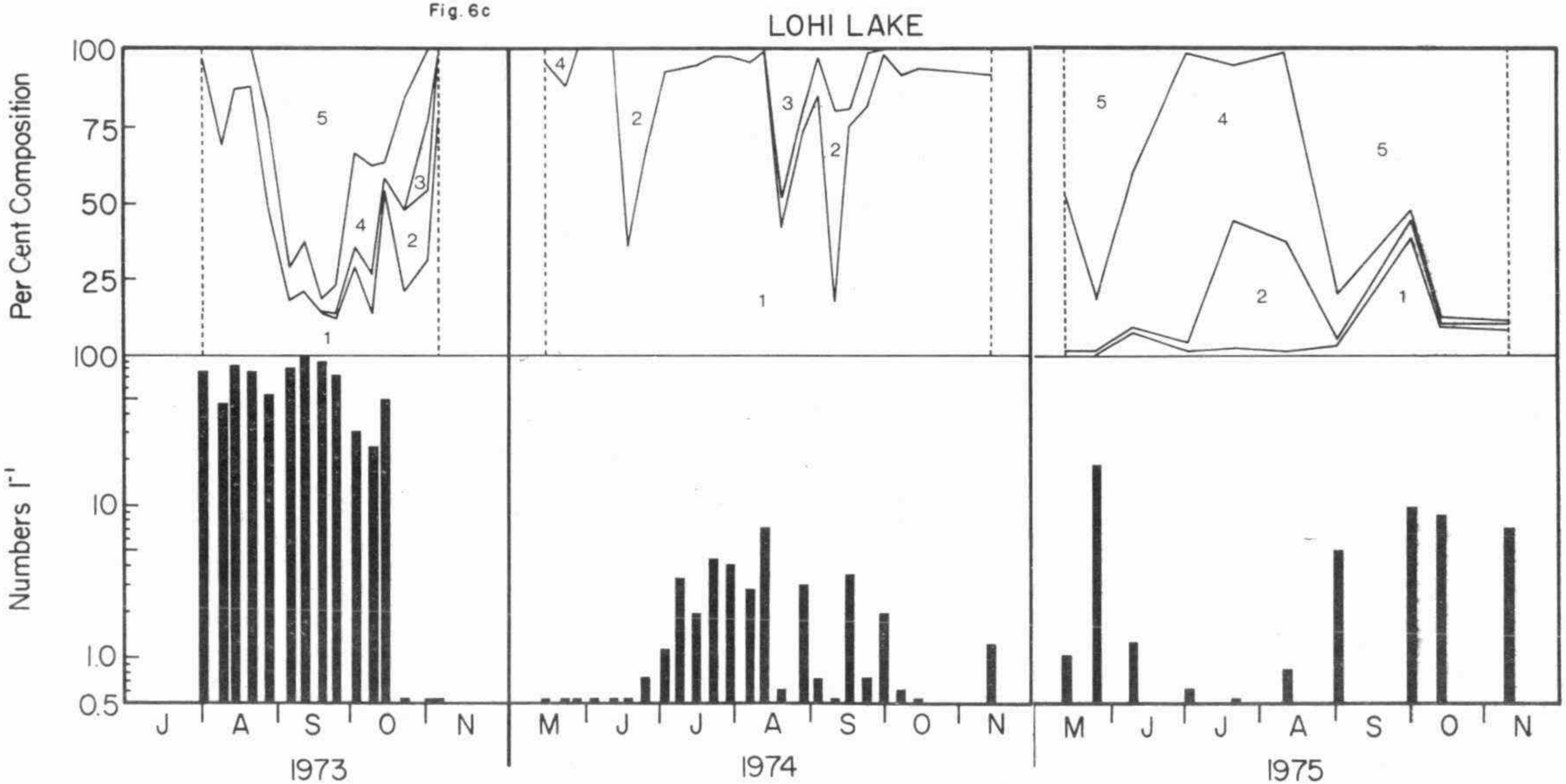
MIDDLE LAKE
Per Cent Composition
100
75
50
25
100
Numbers l⁻¹
10
1.0
0.5
J A S O N
1973
M J J A S O N
1974
M J J A S O N
1975
1
2
3
4
5

Fig. 6b



HANNAH LAKE
Per Cent Composition
100
75
50
25
100
10
1.0
0.5
Numbers l⁻¹
5
4
2
1
3
J
A
S
O
N
M
1973
1974
1975

Fig. 6c



LOHI LAKE
Per Cent Composition
100
75
50
25
100
10
1.0
0.5
Numbers l⁻¹
1
2
3
4
5
J
A
S
O
N
M
1973
1974
1975

Fig. 6d

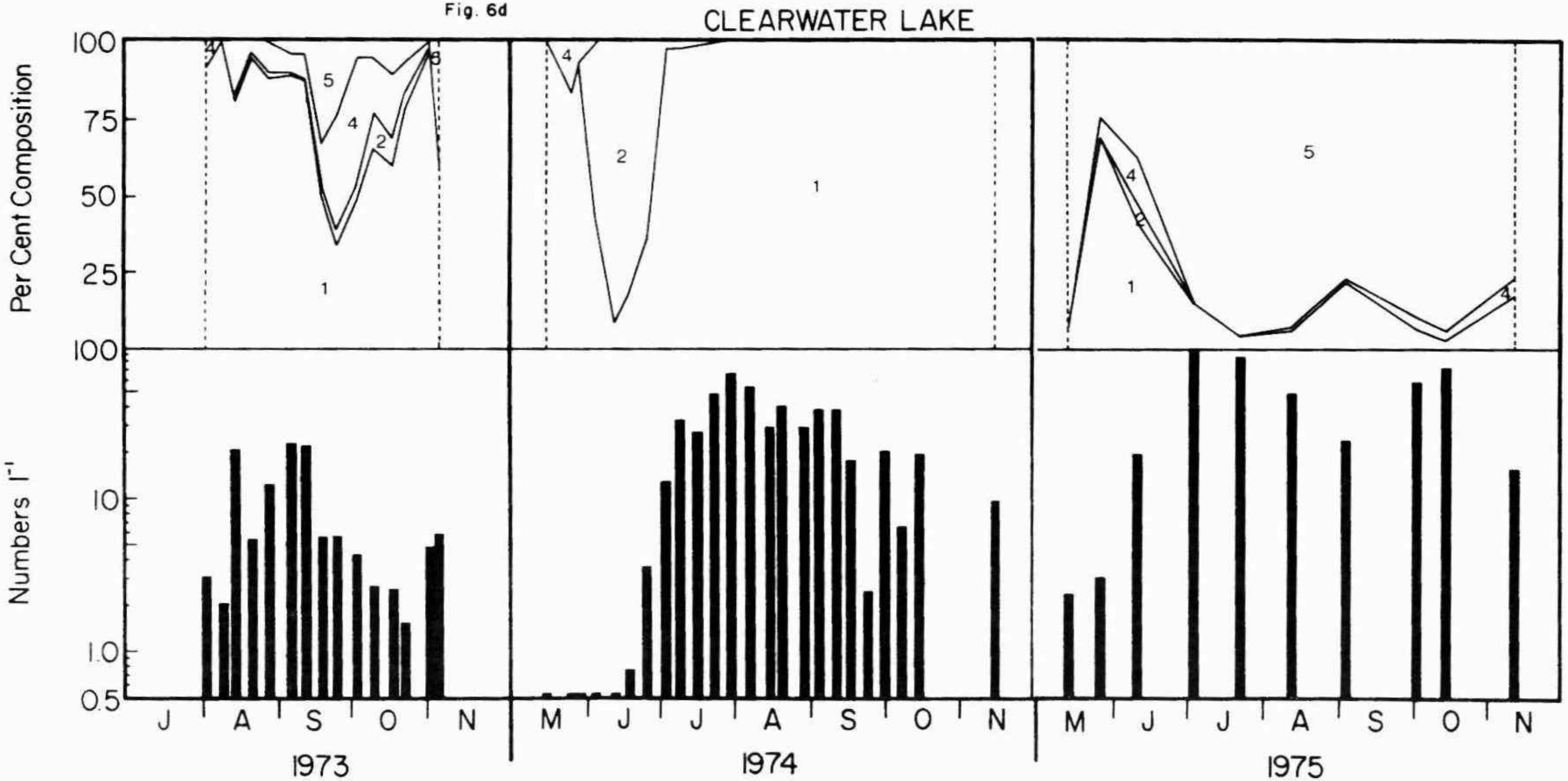
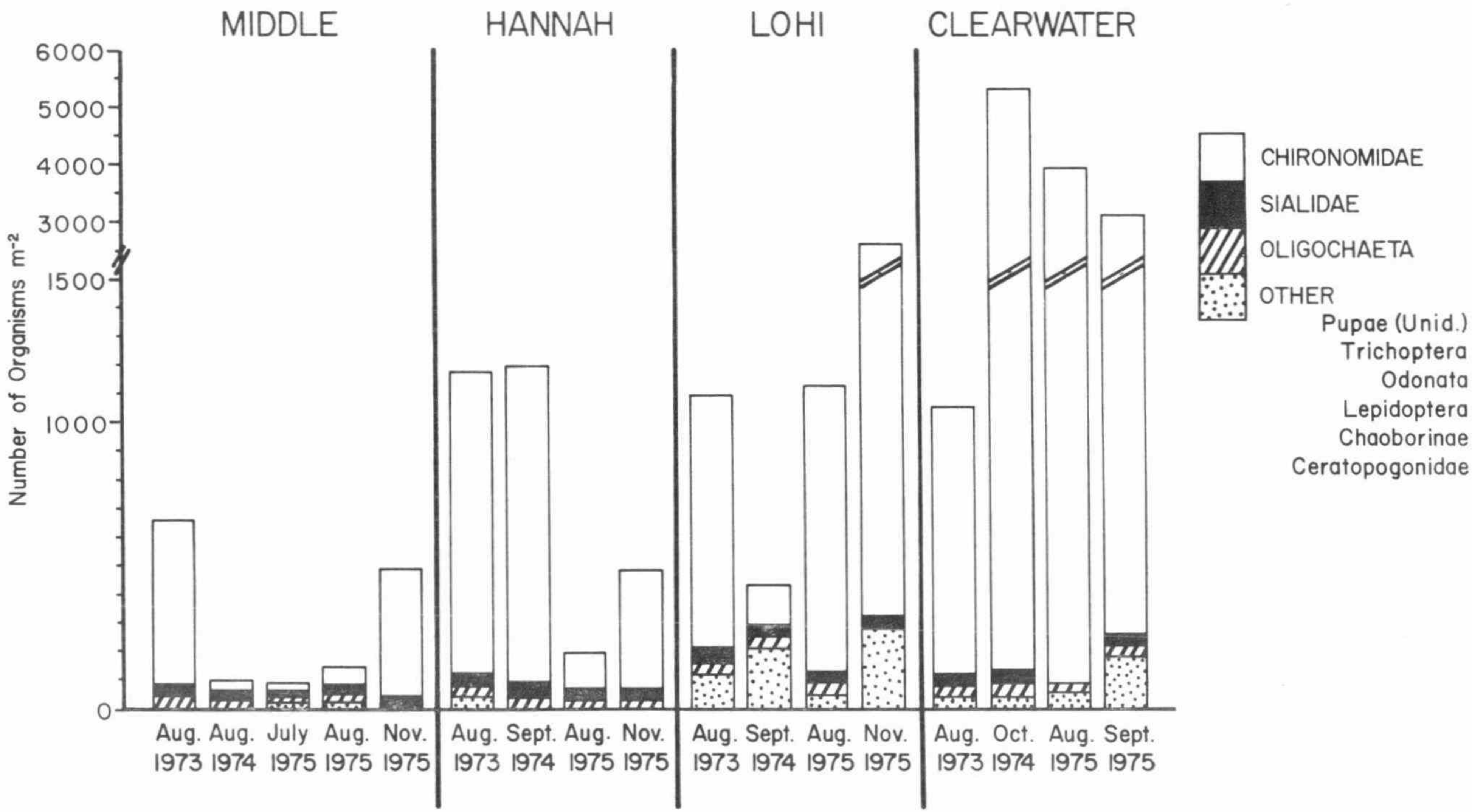

CLEARWATER LAKE
Per Cent Composition
Numbers l⁻¹
100
75
50
25
100
10
1.0
0.5
J A S O N
M J J A S O N
M J J A S O N
1973
1974
1975
1
2
4
5

Fig.7


MIDDLE
HANNAH
LOHI
CLEARWATER
Number of Organisms m⁻²
6000
5000
4000
3000
1500
1000
0
Aug. 1973
Aug. 1974
July 1975
Aug. 1975
Nov. 1975
Aug. 1973
Sept. 1974
Aug. 1975
Nov. 1975
Aug. 1973
Sept. 1974
Aug. 1975
Nov. 1975
Aug. 1973
Oct. 1974
Aug. 1975
Sept. 1975
CHIRONOMIDAE
SIALIDAE
OLIGOCHAETA
OTHER
Pupae (Unid.)
Trichoptera
Odonata
Lepidoptera
Chaoborinae
Ceratopogonidae

ID